

Annual Report

NASA/MSFC Grant NAG8-839

On the Physics of Waves in the Solar Atmosphere:
Wave Heating and Wind Acceleration

Z. E. Musielak

Department of Mechanical and Aerospace Engineering

and

Center for Space Plasma and Aeronomic Research

University of Alabama in Huntsville

August 1993

(NASA-CR-194119) ON THE PHYSICS OF
WAVES IN THE SOLAR ATMOSPHERE: WAVE
HEATING AND WIND ACCELERATION
Annual Report, period ending Aug.
1993 (Alabama Univ.) 8 p

N94-36395

Unclass

G3/92 0013199

CONTINUATION OF STUDIES INITIATED IN 1990

I. Solar Physics

New calculations of the acoustic wave energy fluxes generated in the solar convective zone have been performed by Dr. Z. Musielak in collaboration with Drs. R. Rosner (University of Chicago), R. Stein (Michigan State University), and P. Gail and P. Ulmschneider (University of Heidelberg). The original theory developed by R. Stein in 1967 has been corrected by including a new frequency factor describing temporal variations of the turbulent energy spectrum and a new spatial part of the turbulent energy spectrum. This new spatial part has been obtained by large-scale numerical simulations of convection carried out by Dr. Rosner's group at the University of Chicago. We have also considered two different forms of the frequency factors: Gaussian and modified Gaussian. The original Stein code has been modified by including these new frequency factors and spatial parts of the turbulent energy spectrum, and the code has been tested extensively. The calculated acoustic wave energy fluxes for the Sun are of the order of $10^{7-8} \text{ erg cm}^{-2} \text{ s}^{-1}$ which is smaller than those previously obtained. We have also demonstrated that with the new frequency factors, the calculated acoustic wave energy fluxes are not sensitive to the shape of this factor. One paper containing these results has already been accepted for publication in *The Astrophysical Journal*, another paper is in preparation. The obtained results are important in solving the longstanding problem of solar physics, namely, what is the role of the acoustic wave energy in the heating of the solar atmosphere and in the excitation of the solar p-mode oscillations.

Another possible source of the mechanical energy generated in the solar convective zone is the excitation of magnetic flux tube waves which can carry energy along the tubes far away from the region of their origin. The problem how efficiently these waves are generated in the Sun has been recently solved by Z. Musielak, R. Rosner and P. Ulmschneider.

The obtained results indicate that the magnetic tube wave energy fluxes are sufficient to supply energy to heat lower parts of the solar chromosphere and may be especially important in the energy balance in the chromospheric network. Investigations are being presently performed to estimate how much of this wave energy can reach upper chromospheric layers and also whether these waves can contribute to the heating of the solar corona. One paper on this subject has been just submitted to *The Astrophysical Journal* and two other papers are in preparation.

In order to understand transfer of the wave energy originated in the solar convective zone to the outer atmospheric layers, one has to compute wave propagation and dissipation in highly nonhomogeneous solar atmosphere. This sort of calculations usually requires time-dependent and nonlinear codes. P. Ulmschneider and Z. Musielak have calculated the propagation of nonlinear magnetic tube waves in the solar atmosphere and studied mode coupling, shock formation and heating of the local medium. In a paper recently published in *Astronomy and Astrophysics* we showed that these waves may indeed efficiently heat the solar atmosphere and that the heating will be especially significant in the chromospheric network. Presently, these studies are being extended to include reflection of magnetic tube waves in a more realistic solar atmosphere model.

The propagation of waves in the solar outer atmospheric layers is also important for explaining the observed spectrum of the solar p-mode oscillations. Drs. J. Fontenla (UAH/CSPAR), Z. Musielak and R. Moore (NASA/MSFC) have been working on the wave trapping problems and on evaluation of critical frequencies for wave reflection in the solar atmosphere. The problem of the observed short period tail for the p-mode spectrum is likely to be explained by using these results.

The fact that the solar wind is originated in solar coronal holes has been well-known for many years, however, the mechanism for acceleration of the wind from these holes is still unknown. Also, it is unclear what is the main physical mechanism responsible for

heating of the coronal holes. Recent work done by Drs. R. Moore, Z. Musielak, S. Suess (NASA/MSFC) and C. An (Applied Research, Inc.) has shown that the role played by Alfvén waves in the wind acceleration and the coronal hole heating is dominant. The results of these calculations were already published in *The Astrophysical Journal*. In addition, the authors indicate that the main source of these waves for the heating and the wind acceleration are very likely solar microflares extensively observed in the UVSP data. New extensive studies of the physical processes responsible for the solar wind acceleration are being undertaken as a result of this support. First obtained results are being prepared for publication in *The Journal of Geophysical Research*. We intend to construct self-consistent models of the solar coronal wind based on the reflected Alfvén waves and compare the theoretical range of physical parameters required by these models to observational data.

The results discussed above have been obtained for the Sun. Presently, we are performing calculations of wave energy fluxes generated in late-type dwarf stars and studying physical processes responsible for the heating of stellar chromospheres and coronae. This will allow us to investigate solar-stellar connections.

II. Physics of Waves

A new analytical approach for studying linear Alfvén waves in smoothly nonuniform media has been recently developed by Drs. Z. Musielak, J. Fontenla and R. Moore. The approach formally takes into account continuous, arbitrary structure of the background medium and allows transforming the wave equation to the form of the Klein-Gordon equation which displays a critical frequency for wave propagation. It has been shown that the wave equation can be always transformed to a Klein-Gordon equation and that the latter displays the critical frequency below which reflection is strong; the results of these studies have been recently published in *Physics of Fluids*. This approach is presently being extended to study the propagation of linear and nonlinear magnetohydrodynamic

(MHD) waves in stratified, non-isothermal and solar atmosphere. Dr. Z. Musielak and a graduate student are presently working on developing a numerical code to carry out these calculations and the research is supported by this NASA grant. The motivation for these studies is to investigate in detail the problem of chromospheric and coronal heating, wind acceleration, damping of p-mode oscillations by energy leakage and other problems related to the solar and stellar activity.

Publications Resulting From This Support

- “Why the Winds from Late-Type Giants and Supergiants are Cool”
Moore, L. T., Musielak, Z. E., An, C. H., Rosner, R. and Suess, S. T., *Astronomical Society of the Pacific Conference Series: Cool Stars, Stellar Systems and the Sun*, Eds. M. Giampapa and J. Bookbinder, (1992) p. 464-467.
- “Klein-Gordon Equation for Wave Motions in Nonuniform Media”
Musiak, Z. E., Fontenla, J. M., and R. L. Moore, *Phys. Fluids B*, **4**, 13-18 (1992).
- “A Regularization Method for the Extrapolation of the Solar Potential Magnetic Fields”
Gary, G. A. and Musielak, Z. E., *Astrophys. J.*, **392**, 722-735 (1992).
- “Alfven Wave Trapping and Heating in Coronal Holes: Theory and Observation”
Suess, S. T., Moore, R. L., Musielak, Z. E. and An, C. H., *Solar Wind Seven*, Eds. E. Marsch and R. Schwenn (Pergamon Press) p. 117-120 (1992).
- “Alfven Wave Heating in Solar Coronal Holes”
Moore, R. L., Musielak, Z. E., Suess, S. T. and An, C. H., *Memorie della Societa Astronomica Italiana*, Volume **63**, 777-779 (1992).
- “Heating of Solar and Stellar Chromospheres and Coronae by MHD Waves”
Musiak, Z. E. *Memorie della Societa Astronomica Italiana*, Volume **63**, 635-648 (1992).
- “Heating of Solar and Stellar Chromospheres and Coronae by MHD Waves”
Musiak, Z. E. *Highlights in Astronomy*, Ed. J. Bergeron, Volume **9** (1992) 112-113.
- “A New Way to Convert Alfven Waves into Heat in Solar Coronal Holes: Intermittent Magnetic Levitation”
Moore, R. L., Hammer, R., Musielak, Z. E., Suess, S. T. and C. H. An *Astrophys. J. Letters*, **397**, L55-L58 (1992).
- “The Cutoff Frequency for Fast-Mode Magnetohydrodynamic Waves in an Isothermal Atmosphere with a Uniform Horizontal Magnetic Field”
Stark, B. A. and Musielak, Z. E., *Astrophys. J.*, **409**, 450-454 (1993).
- “On the Heating Mechanism of Coronal Holes”
Hammer, R., Moore, R. L., Musielak, Z. E. and Suess, S. T. *Advances in Stellar and Solar Coronal Physics*, Eds. J. L. Linsky and S. Serio (Kluwer Academic Publication, Dordrecht) (1993) in press.
- “On Sound Generation by Turbulent Convection”
Musiak, Z. E., Rosner, R., Stein, R. F., Ulmschneider, P. and Wang, A., *As-*

- trophys. J.* (1993) in press.
- “On the Origin of “Dividing Lines” for Late-Type Giants and Supergiants”
Rosner, R., Musielak, Z. E., Cattaneo, F., Moore, R. L., and Suess, S. T., *Nature* (1993) - submitted.
- “On Dirac Equations for Linear Magnetoacoustic Waves Propagating in an Isothermal Atmosphere”
Alicki, R., Musielak, Z. E., Sikorski, J., and Makowiec, D. *Astrophys. J.* (1993) - submitted.
- “On the Generation of Flux Tube Waves in Stellar Convection Zones. II. Improved Treatment of Longitudinal Tube Wave Generation”
Musiak, Z. E., Gail, P., Rosner, R., and Ulmschneider, P., *Astrophys. J.* (1993) - submitted.
- “Numerical Studies of MHD Body and Surface Waves: Single Magnetic Interface and Magnetic Slab”
Wu, S. T., Xiao, Y. C., Musielak, Z. E., and Suess, S. T., *Phys. Fluids B* (1993) - submitted.
- “On Reflection of Alfvén Waves in the Solar Wind”
Krogulec, M., Musielak, Z. E., Suess, S. T. and Nerney, S. F. *J. Geophys. Res.* (1993) - submitted.
- “Alfvén Wave Reflection and Its Dependence on Direction of Wave Propagation”
Musiak, Z. E. and R. L. Moore, *Astrophys. J.* (1992) - to be submitted.
- “Dependence of Alfvén Wave Reflection on Direction of Wave Propagation: Klein-Gordon Equation Revisited”
Musiak, Z. E. and R. L. Moore, *Phys. Fluids B* (1992) - to be submitted. - to be submitted to *Phys. Fluids B* in May 1993.
- “Propagation of Nonlinear Longitudinal-Transverse Waves along Magnetic Flux Tubes in the Solar Atmosphere. II. Wave Energy Fluxes”
Huang, P., Musielak, Z. E., and Ulmschneider, P. *Astron. Astrophys.* (1993) - to be submitted.
- “Modified Lighthill Theory of Sound Generation in an Isothermal Medium”
Wang, A., and Musielak, Z. E. *Phys. Fluids A* (1993) - to be submitted.

Presentations Resulting From This Support

"Intermittent Magnetic Levitation and Heating by Alfven Waves in Solar Coronal Holes"

Moore, R. L., Hammer, R., Musielak, Z. E., Suess, S. T., and An, C. H.
Bulletin of the American Astronomical Society, **24** p. 782 (1992).

"On the Heating Mechanisms of Coronal Holes"

Hammer, R., Moore, R. L., Musielak, Z. E., and Suess, S. T.
Symposium on Stellar Coronae, Palermo, Italy, June 1992.

"Propagation Characteristics of Pc3 Compressional Waves Generated at the Dayside Magnetopause"

Zhang, X., Comfort, R. H., Musielak, Z. E., Moore, T. E., Gallagher, D. L. and Green, J. L.
Chapman Conference on Solar Wind Sources of Magnetospheric ULF Waves, Williamsburg VA, Sept. 1992.

"On Sound Generation by Turbulent Convection: A New Look at Old Results"

Musielak, Z. E., Rosner, R., Stein, R. F., Ulmschneider, P., and Wang, A.
AAS Meeting, Phoenix AZ, January 1993. *Bulletin of the American Astronomical Society*, **24** (1992) in press.

"The Role of Non-Linear Alfven Wave Coupling in the Heating of Solar Coronal Holes"

Stark, B. A., Musielak, Z. E., Suess, S. T., and Ulmschneider, P.
AGU Meeting, Baltimore MD, May 1993. *EOS*, **74**, 244, (1993).

"Excitation of Non-Linear Magnetic Tube Waves in the Solar Atmosphere"

Huang, P., Musielak, Z. E., and Ulmschneider, P.
SPD Meeting, San Francisco CA, July 1993. *Bulletin of the American Astronomical Society*, **25** (1993) - in press.

"The Heating of Solar Coronal Holes by Means of Non-Linear Alfven Wave Coupling"

Stark, B. A., Musielak, Z. E., Suess, S. T., and Ulmschneider, P.
SPD Meeting, San Francisco CA, July 1993. *Bulletin of the American Astronomical Society*, **25** (1993) - in press.